An Oscillograph for Ten Thousand Cycles

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Efforts to extend the frequency range of oscillographs have, for the most part, been directed toward increasing the natural frequency of the vibrating element, which has formed the upper limit of the useful range. This paper describes a new method of attack which consists in employing a vibrator strung to only a moderately high natural frequency, and in equalizing the response of the string by electrical circuits both up to and beyond the fundamental resonance frequency. Employing this method of equalization, a galvanometer element has been developed for the rapid record oscillograph which uses strings stretched to a natural frequency of 4500 c.p.s., and equalized to from ten to twelve thousand cycles. The paper concludes with a description of such a modified rapid record oscillograph and with an oscillogram illustrating its use.

IN the past, oscillographs have been employed over a frequency range extending only to a little below the natural frequency of the vibrating element, and efforts to obtain a wider range have been directed toward raising the resonant frequency of the vibrator. In the present paper there is described a new method of attack that obviates many of the difficulties and restrictions previously encountered. In brief it consists in equalizing the natural characteristics of the string by electrical networks inserted in the circuit. One part of the network equalizes for the fundamental resonance F_0, and another equalizes the range above this frequency. Other factors enter to limit the upper frequency obtainable, but practically flat characteristics are secured up to about two and one-half times the fundamental frequency of the vibrator.

The new oscillograph arose from efforts to extend the frequency range of the rapid record oscillograph (Fig. 1) already described.[1] This instrument was of the string type, and before electrical compensation could be applied, a complete study of the string characteristics of the galvanometer was necessary.

If a measurement is made of the deflection of the string by an alternating current of constant value but variable frequency, it is found that the sensitivity increases enormously in the region of its fundamental resonance frequency (F_0) and that there are subsidiary resonance peaks occurring at approximately $3F_0$, $5F_0$, $7F_0$, and so on. No signs of resonance appear at even multiples of the fundamental fre-

[1] *Electronics*, August 1931, p. 70; *Jour. S.M.P.E.*, January, 1932, p. 39; and *Bell Laboratories Record*, August, 1930, p. 580.

Fig. 1—The rapid record oscillograph.

quency. The odd numbered modes of vibration may not be exact multiples of the fundamental because their frequency is influenced by the beam stiffness of the string. With a relatively short, wide ribbon, for example, the third resonance peak may be considerably higher than $3F_0$. The increase in sensitivity in the neighborhood of the various resonance points is accompanied, as with other electrically

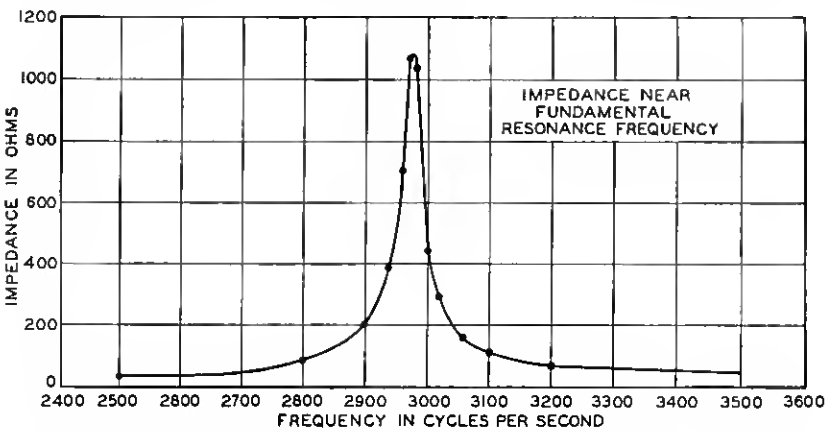

Fig. 2—Variation in impedance near fundamental resonance frequency with image amplitude constant at 2 mm., peak to peak.

driven vibrating systems, by marked variations in the electrical characteristics that the system presents. Measurements of impedance, resistance, and reactance of a rapid record oscillograph galvanometer tuned to 2970 cycles are shown in Figs. 2, 3, and 4, respectively.

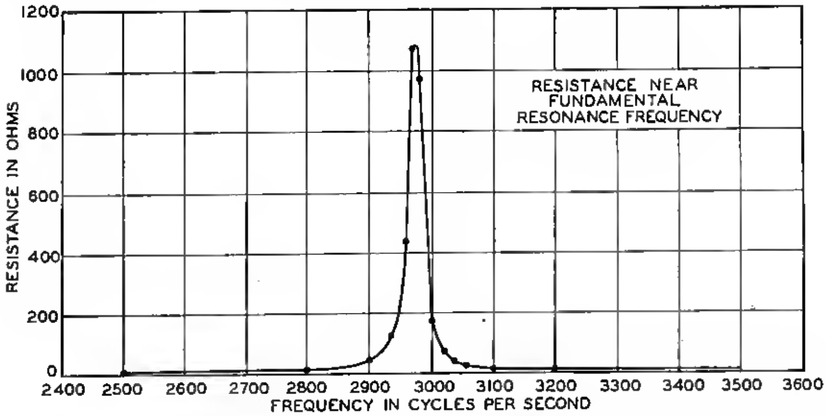

Fig. 3—Variation in resistance near fundamental resonance frequency with image amplitude constant at 2 mm., peak to peak.

If approximate equalization is desired only to a frequency a little below F_0, and if maximum sensitivity is not essential, it is sufficient to shunt the galvanometer with a suitable resistance. Four ohms is about the right value for the instrument under discussion, and gives a deflection vs. frequency curve as shown in Fig. 5. There is a decided peak of sensitivity at $3F_0$ with the result that when a current with a

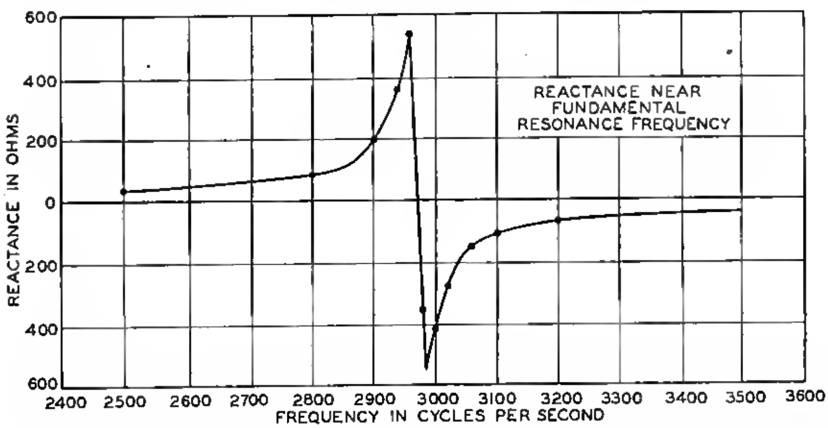

Fig. 4—Variation in reactance near fundamental resonance frequency with image amplitude constant at 2 mm., peak to peak.

square wave front is applied, a weak damped oscillation containing about one cycle of F_0 and many cycles of $3F_0$ will be superposed on the square wave record, as has already been reported by Professor H. B. Williams.[2] The effect of the third partial oscillation is usually of

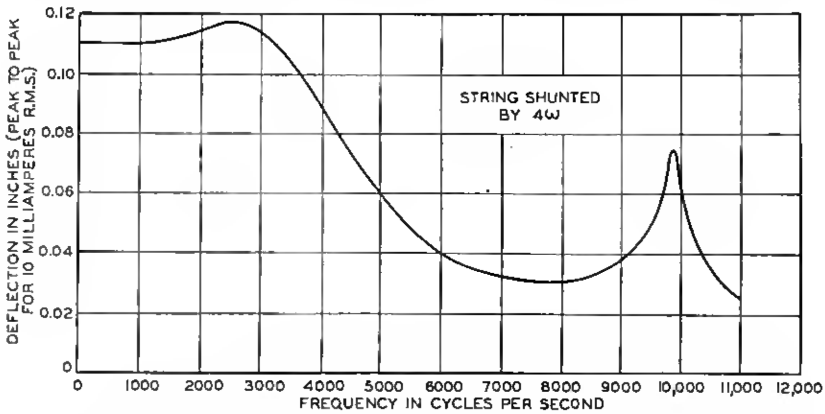

Fig. 5—Characteristics of instrument shunted with a resistance of 4 ohms.

minor importance. Its amplitude is less than the width of the string image, and its effect is noticeable principally as a slight blurring of the trace.

This method of resistance-shunt damping, used with the earlier form of the rapid record oscillograph, gives very satisfactory characteristics up to nearly F_0, but it does not develop maximum sensitivity, which for its attainment requires an equalizing network with characteristics inverse to those of the vibrating string, as described by J. T. Irwin.[3] An inductance in series with a capacitance, which resonates it to F_0, and a suitable resistance are sufficient The characteristics of a string shunted with such an equalizing element, in which for convenience the capacitance was made considerably less than the optimum value, is shown in curve A of Fig. 6. It will be noticed that the deflection for a 10 ma. current has been increased from 0.11 inch, obtained with resistance damping above, to about 0.36 inch—a sensitivity better than three times as great

This type of equalization alone, however, gives a sensitivity at $3F_0$ nearly as great as that at F_0. Because of this there is a greater $3F_0$ distortion with a resonant shunt when a square wave is impressed than with the resistance shunt. The sensitivity at $3F_0$, however, may be damped out by an additional shunt element, and when this is employed the characteristics are as shown by curve B of Fig. 6.

[2] *Jour. Optical Soc.*, September, 1926.
[3] U. S. Patent No. 1,324,054.

With this arrangement the sensitivity falls off rapidly beyond F_0, but recent advances in the art of designing equalizing networks have made it possible to combine with the string already equalized to its

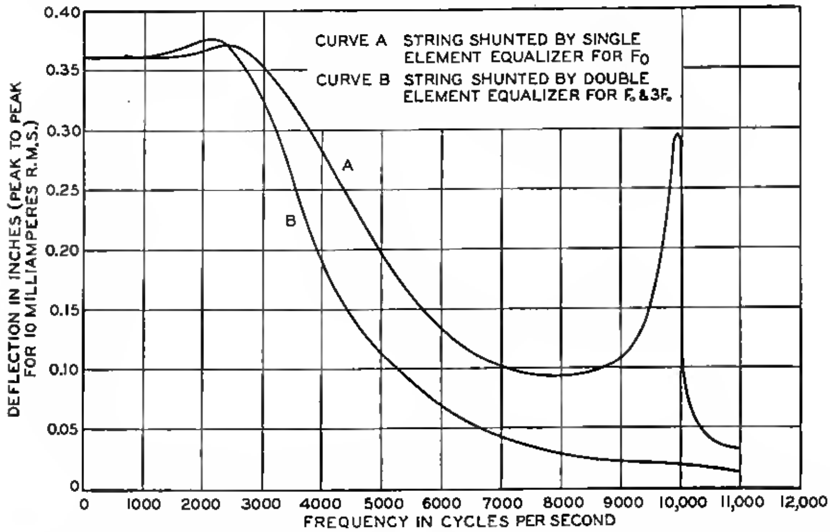

Fig. 6—Characteristics of galvanometer with resonant shunt, alone for curve A, and with an additional shunt to suppress the resonance at $3F_0$, for curve B.

natural frequency of vibration, a second equalizer, designed by E. L. Norton, which extends the range of frequencies through which the deflection is proportional to the current to a point considerably higher than F_0. This is, of course, accomplished at the expense of a corresponding reduction in sensitivity. While a variety of combinations of F_0 and equalizers is possible, a particular case in which a string was tuned to 4500 c.p.s and equalized to 10,000 is illustrated in Fig. 7, which shows the circuit of the equalizer and the characteristic obtained.

As has already been noted, former practice has required an increase of the natural frequency of the vibrator, and the employment of the galvanometer only up to this frequency. Such an increase in natural frequency may be obtained by increasing the tension of the string, by decreasing its mass, by shortening its free length, or by a combination of one or more of these modifications. There are rather severe restrictions to this method, however. Both the diameter to which the wire may be drawn and the stress that may be applied are limited. The string employed for both the earlier and present oscillographs, a duralumin wire 0.0008 inches in diameter, approaches the best available combination of mass and strength, and for the length employed, 6000 cycles is about at the upper limit of fundamental resonance obtainable.

It is possible, of course, to shorten the string and to employ a shorter pole face. Halving the string length might be expected to double the natural frequency, although it would reduce the sensitivity to one quarter its former value. The linearity between deflection and current, however, holds only so long as the deflection is small enough not

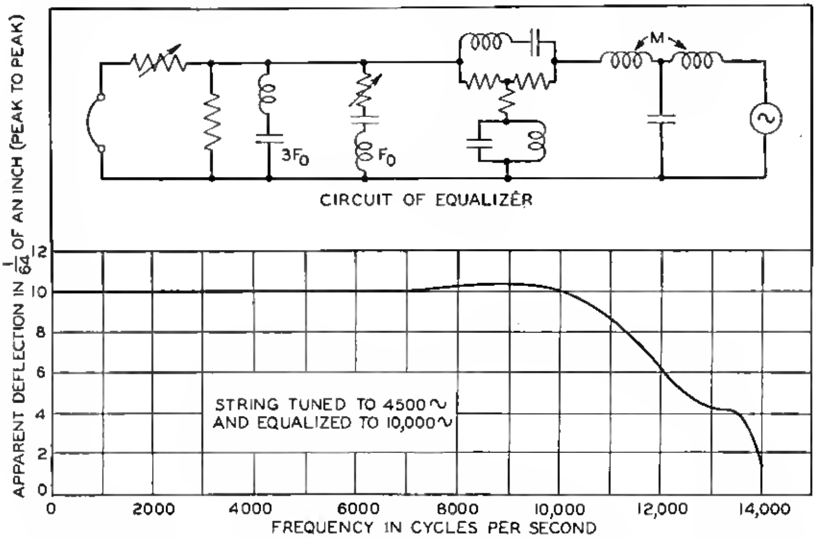

Fig. 7—Equalizing network employed with new oscillograph and the characteristic obtained.

to increase the tension appreciably, so that the shorter the string the less is the permissible deflection. To compensate for this and return to the original size of oscillogram requires an increase in optical magnification, which in turn reduces the transmitted light and thus the speed at which the paper can be exposed. It also increases the width of the string image, which thus becomes a larger proportion of the total deflection, but there is a compensation in that the sensitivity is somewhat increased. Such a design, although capable of responding to a higher frequency, and having a sensitivity greater than that which would be obtained from the shortened string without the additional optical magnification, is less capable of making a photographic record. Actually, with a given string material, light source, and magnetic field strength, there is a definite length of string that will give the widest frequency range both electrically and photographically. It turns out that by using the longer string and the methods of equalization already discussed, the overall sensitivity is about the same as that for the shortened string, and that the optical disadvantages are avoided.

An investigation of how far beyond F_0 the new method of equalization could be employed disclosed certain limitations. In general an increase in frequency range, either by shortening the string or by electrical equalization, reduces the sensitivity, with the result that more current must be passed through the string to secure the desired deflection. Since the heating of the string increases with the square of the current a limit of improvement is ultimately reached. With electrical equalization this limit has been found to be in the neighborhood of $2.5F_0$. A peculiar action of the string in the neighborhood of $3F_0$, described below, would also place an obstacle in the way of equalizing the galvanometer much beyond $2.5F_0$, were the limit not already set by the heating.

When a current remote from $3F_0$ is applied to a string, the deflection is found to be practically proportional to current for all values within the normal range. When a frequency near $3F_0$ is applied, however, the deflection is linear for very small deflections, but at a certain critical value becomes non-linear—increasing very rapidly to from two to three times its previous value. Beyond this point the deflection again becomes linear with current. As the current is decreased, the deflection decreases linearly to approximately the critical value and then decreases abruptly. It does not follow the curve of increasing current, however, but actually forms a hysteresis loop. The phenomenon is shown in Fig. 8. With a frequency of 2000 cycles the deflection

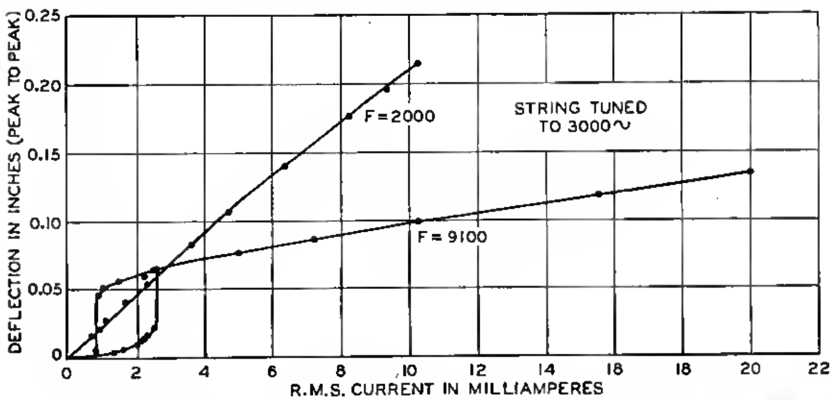

Fig. 8—Deflection-current characteristics for strings tuned to 3000 cycles for frequencies near and remote from $3F_0$.

is practically linear with current for all values, but for a frequency of 9100 cycles, approximately $3F_0$, the hysteresis loop occurs. This discontinuity is greatest at $3F_0$ but is detectable at frequencies several

hundred cycles above or below that value. The change from low to high amplitude or vice versa, although apparently instantaneous, actually lasts about a hundredth of a second. Although no satisfactory explanation has been reached, this phenomenon may be associated with the method of supporting and stretching the string. Its study and elimination would become important, however, only should some means become available of permitting the string to carry several times the present maximum current without overheating—as might be possible if an alloy should be developed with the mechanical properties of duralumin and the conductivity of copper.

The amount of phase distortion present with these various methods of damping and equalizing is difficult to measure directly for frequencies much above F_0. A measurement up to about 4000 cycles was obtained with a two-string galvanometer arranged for somewhat shorter strings than those usually employed with an F_0 of 3200 cycles. One of the strings was stretched to an F_0 of 6000 cycles and left undamped except by air friction. Its phase distortion was computed and is plotted as the lower curve of Fig. 9. The other string was stretched

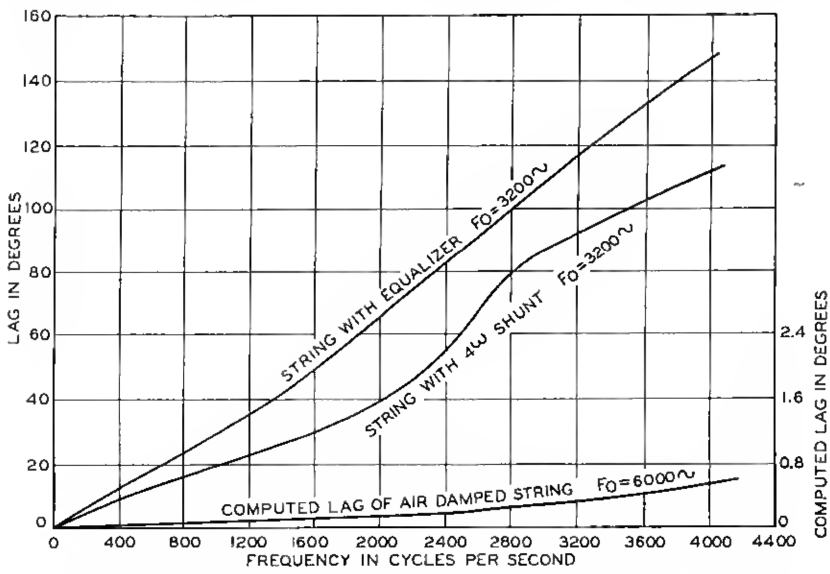

Fig. 9—Phase distortion with equalized and resistance damped strings up to about F_0.

to an F_0 of 3200 cycles, and equalized for the fundamental and third harmonic as already described. Both strings were fed from the same oscillator, and a series of oscillograms taken from 50 to 4000 cycles. The phase shift between the strings was then measured and is plotted

as the upper curve of Fig. 9. As may be seen here, it was found to be nearly linear—with a maximum deviation of about 10°. When the experiment was repeated with a string that was resistance damped, considerable phase distortion was found as shown by the middle curve of the plot.

This method of measurement cannot be used for much higher frequencies because of the difficulty of stretching a string to appreciably more than 6000 cycles. The amount of the phase distortion in an instrument equalized to higher frequencies may be judged, however, by taking oscillograms of square-front flat-topped waves and noting the irregularities produced. The phase correction required was determined by making such oscillograms with a resistance-capacity phase corrector in the circuit, and adjusting the phase corrector to bring about a minimum amount of distortion. An electrical equivalent of this experimental network, giving the same phase correction but with negligible attenuation, is included as part of the equalizing circuit of the new oscillograph. Although it is realized that the resulting phase characteristics are not perfect up to 10,000 cycles, the oscillogram of Fig. 10 shows that there is no great amount of phase distortion present. It has been found that the amount of distortion indicated here is not usually of practical importance.

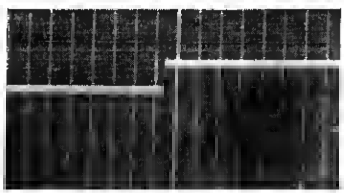

Fig. 10—Oscillogram of square front, flat top wave from an instrument tuned to 4500 cycles and equalized to 10,000. Abscissa divisions are .001 second.

A few years ago a recording oscillograph, of the string type, was developed by Bell Telephone Laboratories, which would satisfactorily record frequencies over the part of the voice range important in telephone work. It represented a distinct advance over the oscillograph of similar type developed during the war for locating enemy guns by sound ranging and improved subsequently for studying circuit phenomena. This earlier oscillograph [4] would record frequencies up to 200 cycles per second and had facilities for developing and fixing the paper record at the rate at which it was exposed, while the improved oscillograph increased the frequency range to 3000 cycles. Although

[4] *Bell Laboratories Record*, March 1927, p. 225.

it also provided for developing the paper immediately after exposure, the rate of development had to be slower than that of exposure because of the very high speed of the paper necessitated by the higher frequencies recorded.

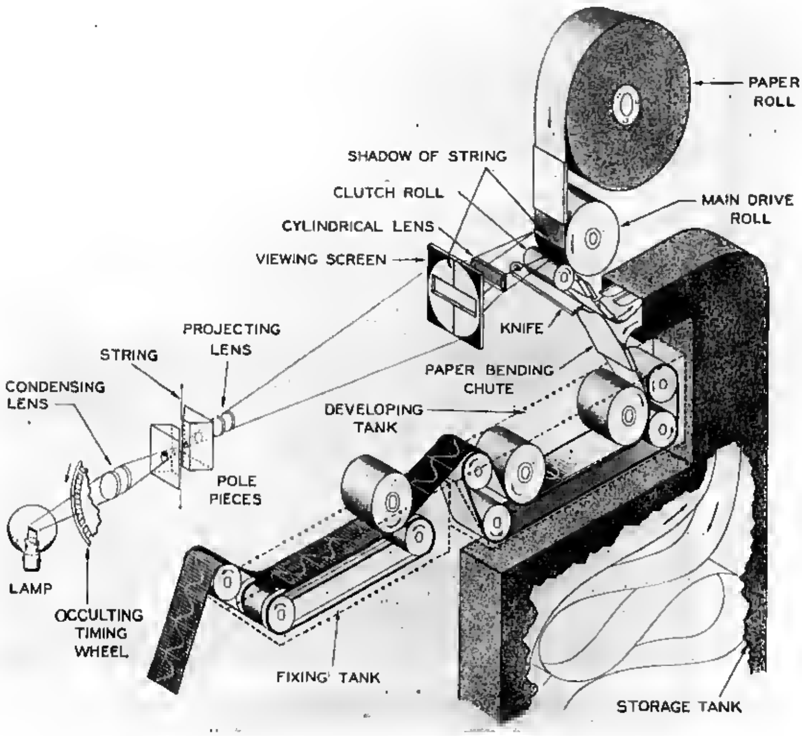

Fig. 11—Diagrammatic arrangement of the new rapid record oscillograph.

This improved instrument, christened the rapid record oscillograph, proved greatly superior to other available equipment and has been used extensively in the varied work of Bell Telephone Laboratories. Recently the galvanometer of this oscillograph has been redesigned, employing the electrical methods of equalization already discussed, and in its present form has a frequency range extending up to ten or twelve thousand cycles per second. With this new equipment most of the components of speech and music may be recorded.

Its arrangement is shown in the schematic photograph of Fig. 11. Light from the lamp at the left is focussed by the condensing lens on the strings of the instrument through the perforated pole piece. Only

one of the two or three strings provided is shown on the diagram. The images of the strings are focussed by the projecting lens onto the sensitized paper used for the record, where they appear as shadows on a light background. An achromatic cylindrical lens in front of the paper further focusses the light into a narrow band with a width of a

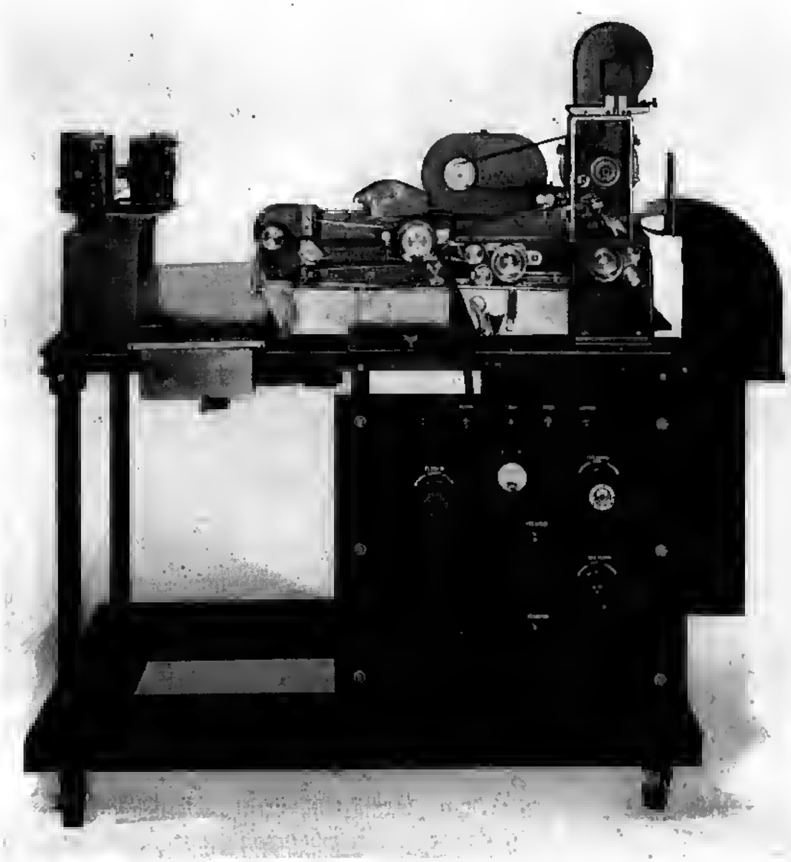

Fig. 12—Rapid record oscillograph. Front view with mechanism exposed. The developing and fixing tanks may be dropped in a few seconds when required.

few thousandths of an inch on which the shadows of the strings fall. As the paper is drawn through the machine, the shadows of the vibrating strings thus photograph on it a trace of the motion of the middle of the string.

Between the lamp and the condensing lens is a timing wheel whose rotation is controlled by an electrically driven tuning fork. Spokes

of the wheel interrupt the light from the lamp every thousandth of a second and thus trace timing lines across the sensitized paper. Every tenth spoke is thicker than the intermediate ones to indicate with a heavier line the hundredths second divisions. Rulings on the cylindrical lens mark horizontal lines a twentieth of an inch apart on the exposed paper to give a convenient measure of the amplitudes of the oscillations.

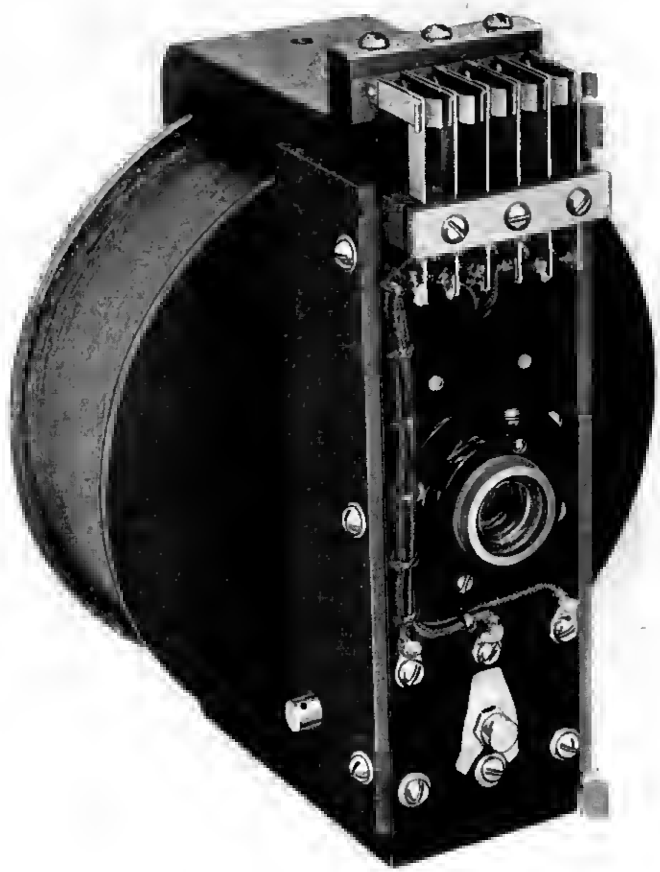

Fig. 13—Galvanometer element of rapid record oscillograph.

Two motors operate the exposing, and the developing and fixing mechanisms. One rotates the main drive roll, which pulls the strip of paper from the unexposed roll through the light beam, and pushes

it into the developing tank. The second carries the paper through the developing and fixing tanks. Each is adjustable in speed and controlled separately. The speed of the main drive motor is adjusted to best exhibit the phenomena that are being observed. Maximum speed is about 130 inches per second, which gives a little over a hundredth of an inch between crests of a 12,000 cycle wave. The motor controlling the developing equipment is adjustable to give paper speeds from two to ten inches a second. The faster the speed at which the paper is exposed the more slowly will it be developed.

Since the paper being exposed is moving faster than that being developed, a storage reservoir for undeveloped paper is provided as indicated in the illustration. At the beginning of an oscillogram the paper is pushed by the main drive roll in between the drive rolls of the developing tank. Since these carry the paper at a lower speed than the main drive, a loop of paper is formed between the two drive rolls which passes into the storage tank. The amount of paper that can be stored depends on the speed of exposure, and varies inversely with it. At low speed the paper settles compactly in the tank and an entire 250 foot roll may be stored. At high speeds the paper does not have time to settle properly, and only about fifty-five feet, corresponding to about five seconds exposure, can be held.

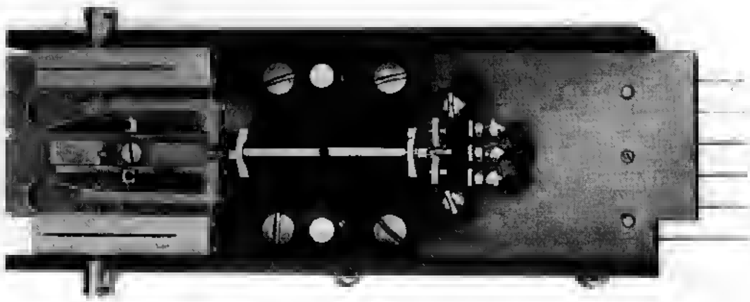

Fig. 14—Rapid record oscillograph. Front pole face of galvanometer. Terminals for the three-string elements are brought to knife contacts, which allows the string mounting and pole piece to be readily removed from the galvanometer.

Both motors having been started, operation of the oscillograph is commenced by pulling out a lever which withdraws a knife blade from the paper, and moves an idler pulley, which presses the paper against the main drive roll. The paper is then run through the storage tank, and the developing and fixing tanks as already described. After the

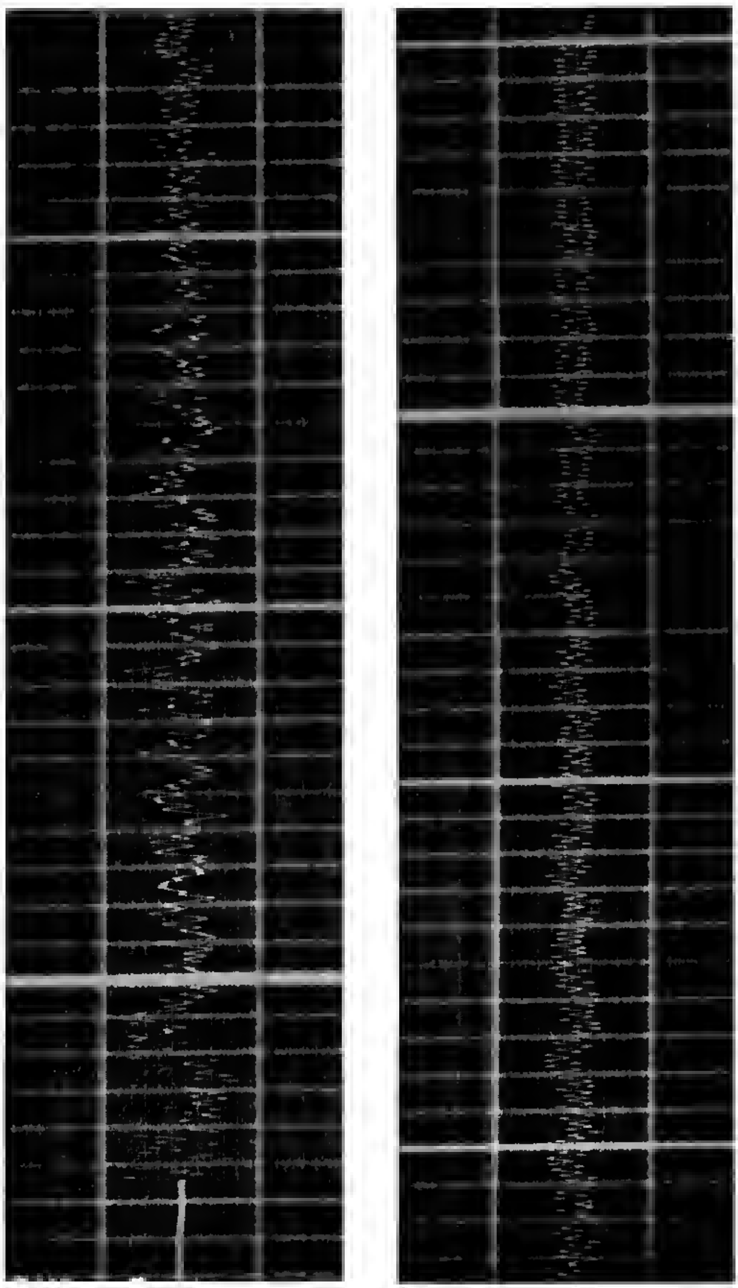

Fig. 15—Sound radiated by a gong struck once, recorded on rapid record oscillograph equalized to 7500 c.p.s. The 6000 c.p.s. tone continues for several seconds more. Abscissa divisions are .001 second.

events under observation have been recorded the starting lever is pushed back, withdrawing the idler pulley from the main drive roll, and releasing the knife, which cuts off the exposed section of paper. An electromagnetic brake, operated by a timing control circuit, is momentarily applied to the spinning roll of paper, and stops it in a fraction of a revolution. The exposed paper continues to pass through the developing and fixing tanks, and into the rinsing tank until it has all been developed. A view of the machine with the developing and fixing tanks dropped for inspection of the mechanism is shown in Fig. 12. A solenoid may be provided for operating the machine from a distance when desired.

The complete galvanometer element of the three-string model is shown in Fig. 13, and one pole piece and the string mounting, in Fig. 14.

As an illustration of the many uses of the new oscillograph, an oscillogram is given in Fig. 15, which shows the wave form of the sound radiated from the gong of a telephone ringer struck once by the clapper. The sound was picked up by a dynamic type microphone, and the resulting current was amplified and fed to a rapid record oscillograph tuned to 4000 cycles and equalized to 7500. The entire system was reasonably distortionless from 30 to 8000 cycles per second. It is interesting to note that the predominant frequency, about 6000 cycles per second, would not have been detected had the record been made with the older types of oscillographs.